Enabling Sustainable Sensing in Adverse Environments

Josiah Hester, Trae King, Alex Propst, Kalyan Piratla, Jacob Sorber
Department of Computer Science
Clemson University
Clemson, South Carolina
{jhester, lking2, japrops, kpiratl, jsorber}@clemson.edu

***Abstract*—Water infrastructure has been degrading on a national scale in the U.S. for years. Much of this degradation is caused by massive leakage in aging water mains. Water is a critical, and finite resource, early identification of these leaks would not only save cities millions of dollars in revenue but also safeguard our limited natural resources. Current methods of leak detection are either too costly, unscalable, or only feasible in the short-term. We propose using environmentally powered embedded adaptive sensors to provide cost-effective water-monitoring infrastructure that can operate maintenance free for the lifetime of a water main. In this poster we will present our early monitoring system, and initial results and analysis from our current deployment in the Clemson University water distribution network. We also present future directions and key research questions.**

I. Introduction

Water infrastructure has been degrading on a national scale in the U.S. for years. Much of this degradation is caused by massive leakage in aging water mains. Unaccounted water loss in the mainland United States is typically reported to range between 15% and 25%, of which about 60-75% is recoverable leakage [1]. Nearly seven billion gallons of treated water is lost per day, nationwide, at an energy cost of roughly 3.85 GW-h, and revenue cost in the tens of billions. However, the government is not in a position to invest the amount required to completely replace the current water distribution infrastructure, and instead must rely on new, more cost effective ways to augment the current system, that focus on early leak detection.

Leak detection has traditionally relied on acoustic techniques to identify faulty pipes, but these techniques and the tools that go along with them require expert training to manage and use, and taking measurements can be time consuming. While reliable, they are impractical from a cost standpoint for the amount of pipe infrastructure that exists even in a small town. Other solutions have involved inserting devices such as micro water turbines inside of the pipes themselves [2], but because of the sensitive nature of water, the work required, and the high cost of turbine devices, these have proved impractical.

To solve this problem, we need real time, non-intrusive monitoring of the entire pipe network. The ideal system would monitor changes in water pressure and react accordingly either by notifying observers, or by autonomously shutting off sections of the water grid for maintenance. Prediction and early detection of leaks would save cities millions of dollars a year in revenue. However, designing such a system presents many challenges, as it must have a low environmental impact, be extremely fault tolerant, and be able to monitor and communicate using very low amounts of inconsistent power. Durable low cost, environmentally powered sensors could enable this type of system. This is an ambitious, multi-year project, and will require modeling, engineering and data collection beyond the scope of this paper. Our main contributions are collection and interrogation of foundational data, and identification of challenges, key questions, and research directions.

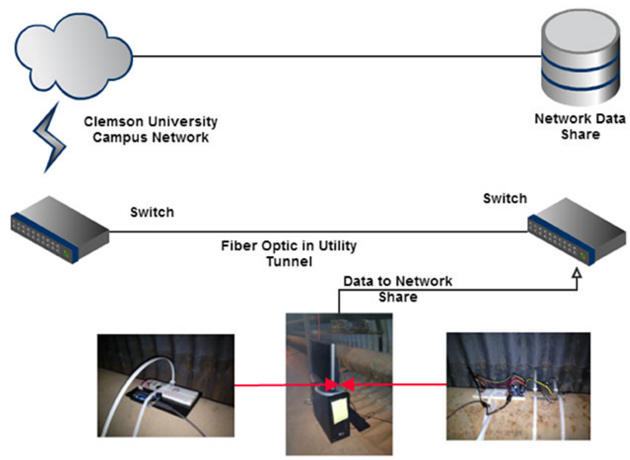

Fig. 1. Current Pipeline Remote Data Acquisition System with two sensing endpoints over a 10-foot area of pipeline. Future setups will cover over 100 foot of pipeline.

In this poster we will present the hardware and software of a high frequency, vibration and acceleration sensing platform installed on one of the many subterranean water lines supplying Clemson University. We will also present vibration and acceleration data gathered from two weeks of deployment, and use this data to identify methods for transient event detection, and characterize the potential harvestable energy. Additionally we present our key questions and research directions.

II. Pipeline Monitoring Testbed

In order to assess the energy harvesting potential of an average water main, and the relationship between hydraulic changes within the pipelines and surface vibrations, we deployed a custom remote data acquisition system on a major water main running in an underground tunnel system underneath Clemson University. To enable fast data acquisition from a remote

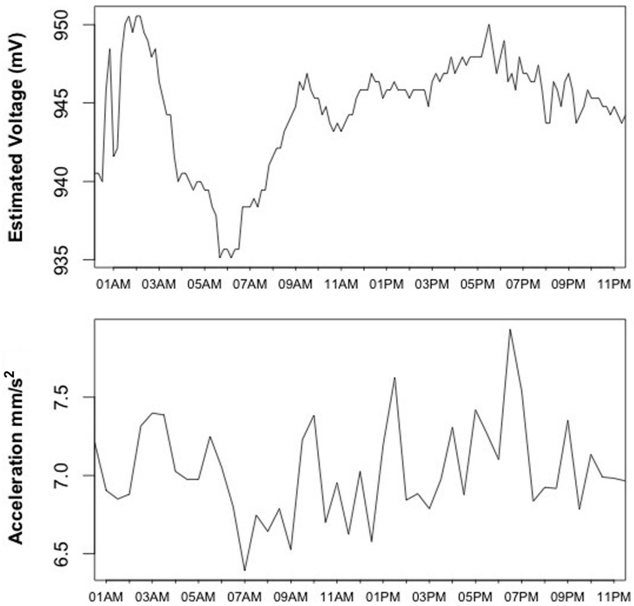

Fig. 2. Top: Piezo readings converted to voltage, RMS over 10 minutes in a 24 hour window for Thursday, April 25th. Bottom: Acceleration in the X-Axis, RMS over 30 minutes in a 24 hour window for Thursday, April 25th.

location, we ran a fiber optic jumper from the networking core of the nearest building to our data collection site about 300 ft down the underground tunnel. At the data collection site, we connected a 10-port ethernet switch to the fiber jumper, giving us plenty of networking options for future setups.

The network access at our deployment site made it possible to install a semipermanent system to collect data continuously and store the data in shared network storage. For this we used a standard desktop computer with a ethernet connection to campus to serve as a data collection server. For the sensor systems, we used 2 Arduino Uno prototyping boards to sample a set of sensors and relay the data over the serial port to the data collection server. One of the prototyping boards was wired to a Minisense 100 piezo sensor, mounted perpendicular to the water flow on top of the pipe. The piezo sensor was sampled as fast as possible (587 Hz) and transmitted the vibration data over serial to the data collection server. Exactly 10 feet down the pipe from the first Arduino Uno, we placed the second Arduino Uno in the same position on the pipe, connected to an ADXL335 accelerometer. The accelerometer was sampled as fast as possible (125 Hz), also transmitting its data over serial to the data collection server–this yielded about 50 million readings for the piezo sensor per day and about 10 million accelerometer readings per day. The primary reason for sampling data at such a high frequency was to collect as much high frequency vibration data as possible in order to gain a more complete understanding of the variation we may see for any given time period along the water main.

By using two sensor types we hope to better characterize what is actually going on inside the pipeline, our current setup is easily extensible from a hardware perspective, and the remote access allows us to easily reprogram all the devices, run diagnostics, and gather data all from outside the tunnel.

III. Experimental Results

Our first experiments focused on establishing a baseline on which we could compare traces of potential leaks. Since we had no ground truth data defining pressure and flow at discrete areas of the pipeline, we had to create the ground truth ourselves. It has been proven theoretically that variation in surface acceleration is proportional to the variation in pressure and flow as shown in Equation 1[3]:

$$\Delta a = -\frac{g}{A\gamma}\Delta P \tag{1}$$

Where a is the surface acceleration on the pipes; g is the acceleration of gravity; γ is the specific weight of the fluid-filled piping system, and P is the pressure in the pipeline. From this (unverified) model we can assume acceleration events picked up by sensors on the pipe will give a good approximation to the circumstances (pressure and flow) in the interior of the pipeline. Since water leaks typically correspond to a instantaneous dramatic decrease in water pressure and flow, we can assume from this equation that dramatic decreases in surface vibration are leak indicators. Before we knew what a ”dramatic” decrease in flow meant, we had to catalog normal water variation in our experimental testbed. From data gathered in our initial deployment and in preliminary deployments, we were able to estimate the rate and magnitude of harvestable piezoelectric energy on a section of pipeline, after acquiring this baseline we used the macro view of our data to identify events over the course of a day, with an emphasis on events that occurred daily throughout the week. We were able to gather nearly 360 million observations of the pipeline, consisting of accelerometer and vibration readings, over the course of six days from April 20th to April 25th. Because of the magnitude of the data points we used Root Mean Square over one, ten, twenty, and sixty minute increments to offer a macro view of the variation in the pipeline throughout the day.

From the acceleration and vibration traces, it is obvious that specific flow events happen throughout the day. During the intervals from 7am-10am on each day gathered, we found a steady increase in the acceleration and therefore flow in the pipes, this event correlates strongly to when students arrive on campus, and when the majority of water use would begin to start during the day. This event observation is corroborated by both the vibration and acceleration data, with transitions of similar magnitude shown in both. Now that we know these macro level events are happening consistently through the day, and that vibrations predict flow with reasonable accuracy, this lays the groundwork for effective monitoring of the pipe system with transient devices.

IV. Future Directions

This is an ambitious, multifaceted project, with many potential directions, our work has laid the groundwork for future research, and provided a data acquisition platform and testbed to implement our ideas and test their efficacy. We have identified three key areas to focus on, characterizing the energy harvesting abilities, solving transience, and detecting leaks.

A. Energy Harvesting Characterization

While we have been able to get rough estimates of the energy harvestable from a water pipeline, we have not conducted full experiments yet on our testbed. Because the energy available will most surely be very low, we will be exploring custom harvester designs that are better suited for our scenario. We would also like to characterize the general availability of energy, by understanding what events or times of day seem to be the most energetic and when we can expect little to no harvestable energy.

B. Adaptive Computing Strategies for Transient Power

When sensors are deployed on a underground water main, it will be impossible to change batteries or conduct maintenance of any kind. We can use a combination of hardware and software strategies to increase the lifetime of the individual sensors, and the network as a whole. Drawing on related platforms such as the Moo[4], we hope to reduce power consumption, while not interrupting important computation. Because their is a high likelihood that programs will take more time than the energy budget allows, we will have to figure out an effective recovery method. Mementos solves this transient power problem completely in software by calculating power supply at compile time and runtime and then using this information to make decisions on when to checkpoint programs before a power loss [5]. As we have observed in the data traces, the pipeline flow from a macro level is fairly regular, with areas of time that have increased flow, and other areas that are low in pressure and flow. Because of the timing based nature of water distribution networks, an iterative energy aware task scheduler such as Dewrop could be a part of the solution to account for transient energy [6]. To reduce power consumption by reducing total awake time we would also like to explore hardware analog filtering methods similar to Hibernets [7], which filters out signal on the hardware level so that our micro controller can only be woken up to perform computation when absolutely necessary.

C. Detecting leaks on transient power

Our current monitoring platform has been instrumental in collecting the ground truth observations of a typical water main. The next step will be using this data to identify the vibration and acceleration profile of a leak. During the course of this research we will be working with the Clemson-Anderson water utility to characterize events that happen in the pipeline, relative to the vibrational energy and acceleration they produce. We would like to see the vibration profile of what something as simple as opening a hydrant on campus looks like. Once we run these tests we will have a better idea of what we are looking for in terms of leaks. From there our challenge will be to determine the minimum amount of processing and time that a sensor must be on to facilitate the data capture of these leaks and the communication back to the monitoring station.

V. Conclusions

Most of our water infrastructure is decades old, and in some places falling apart. Cities lose millions in water revenues every year but don't have the capacity to fix the problem. Long term monitoring of water infrastructure with embedded adaptive sensors to enable leak detection provides a cheap way to extend the life of our pipelines and minimize the amount of leakage of one our most precious natural resources. This system would have to have rich processing abilities but on a very minimal energy budget. It would need to be able to react to low power and no power situations in such a way as not to interrupt the function of the system, all with a lifetime measured in the decades. Such a system would be widely applicable not only to pipeline monitoring, but to other situations which require long lived, low impact sensing platforms.

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